Plant-soil interactions in multi-strata agroforestry systems with perennial crops

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Introduction

Multi-strata agroforestry systems with perennial crops are wide-spread in the more humid regions of the tropics. They comprise a continuum ranging from small-scale, sometimes highly diversified associations of tree crops which are managed for family consumption and local markets (e.g., homegardens), to export-oriented plantations of the major agricultural crops of the world such as coffee, cocoa and tea if these are grown under shade trees. Research on plant-soil interactions in agroforestry with perennial crops has largely concentrated on the second type of systems, presumably both because of their higher economical interest and their simpler structure. The complex nature of the homegarden-like systems is in fact a major obstacle to the conduction of research on plant-soil interactions, because the spatial heterogeneity of the systems makes it difficult both to obtain and to interpret representative soil data for a system as a whole. However, for the supply of small farmers with little access to the international markets with food and some cash; for the conservation of germplasm diversity of tree crop species of lesser importance; and for the maintenance of a diversity of niches for the fauna and flora in an agricultural landscape, these highly diverse systems may be of considerable importance. They consequently merit research efforts for their understanding and improvement. In this review, we try to organize the available information on plant-soil interactions in multi-strata agroforestry with perennial crops with the objective of developing strategies for the optimization of resource use and the maximization of environmental benefits of such systems.

Two approaches to the analysis of complex agroforestry systems

As in the past research on complex agroforestry systems has suffered from the difficulty of dealing with their complexity, we first discuss two approaches to their analysis.

The first approach is to compare a plot (or a number of plots) under multi-strata agroforestry with control plots under simpler agricultural systems, e.g. the monocultures of one or several of the components of the agroforestry system. The variables to be compared could be the average soil fertility as measured on representative samples from the whole plots, or the water and dissolved nutrient yield from micro-catchments covered with the respective system types. This approach is necessary for the evaluation of the total environmental costs and benefits of a system; however, the information obtained is very specific for the studied systems and gives little information on how its characteristics would be affected if one crop species or management measure was exchanged by another, or how the system could be improved with respect to a certain characteristic.

The second approach is the analysis of the within-plot heterogeneity of a complex agroforestry system in relation to the crop species present and their respective management. The variables

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measured could include the soil fertility or the quantity and composition of the infiltrating soil water under the different species within an agroforestry system (analysis of "single-tree effects"). This second approach is common in forest and savanna ecology, but has until recently not been applied systematically in the study of agroforestry systems with perennial crops. The information obtained is less representative for the total system than that obtained with the first approach, but has the advantage that the effects of the integration of a certain plant species or of the application of a management measure can be identified from the within-plot heterogeneity that they cause. As a consequence, species and management practices can be identified which allow to direct the system's properties into a certain direction, e.g. towards more efficient nutrient cycling, higher diversity of the soil fauna etc. The results are more difficult to scale up, but are easier to transform into practical recommendations.

Optimizing plant-soil and plant-plant interactions in multi-strata agroforestry

Increasing soil fertility during the establishment phase

Tree crops often take several years before they begin to produce. This makes it difficult for small farmers to invest into their optimum establishment, for example by rising the fertility of chemically impoverished soils, planting a leguminous cover crop and regular weeding of the young trees. Poor development conditions of the trees can slow down their vegetative growth, delay the beginning of the production phase and reduce yields. In Amazonia, young tree crops are often initially associated with unfertilized food crops such as cassava. After its harvest, they suffer from the competition of a developing fallow vegetation. The association with annual or semi-perennial species of high market value could help to rentabilize rapidly investments made into the young plantation, from which the tree crops may profit for several years. An example from central Amazonia shows that the fertilization applied to papaya (*Carica papaya*) which was grown in the interrows of a multi-strata agroforestry system with cupuaçu (*Theobroma grandiflorum*), peachpalm (*Bactris gasipaes*) and rubber trees (*Hevea* sp.) increased the levels of available P and cations in the soil until several years after the papaya had been removed. It also improved the development of the leguminous cover crop and the vegetative development, precocity and yields of cupuaçu. This shows that, with sufficient market access, farmers could recapitalize the soil fertility of their plantations on the medium term through relatively short-term investments into the management of semi-perennial crops.

Increasing the efficiency of nutrient cycling within the system

Due to their perennial nature, systems based on tree crops such as multi-strata agroforestry should have efficient nutrient cycling mechanisms. However, these systems often grow on soils with high water permeability (e.g. Oxisols) and under high rainfall conditions. Studies in central Amazonia revealed subsoil accumulations of nitrate as evidence for N leaching also under multi-strata agroforestry. The accumulation differed between tree species within the system, indicating that leaching losses could be reduced through changes in systems design and management. Optimizing systems with respect to efficient nutrient use requires information on the zone from which nutrients are taken up by different plant species. These are only available for a few tropical tree crops.

In the clayey soils of central Amazonia, N mineralization rates can be high, and the efficient use of this native N in agroforestry systems may be more important than the increase of N inputs from N-fixing plant species. Particularly high mineralization rates and N losses into the subsoil have been observed under leguminous cover crops. Through improved systems design and management of the cover crop, the efficiency with which this N is used by the tree crops could be increased, thereby reducing the dependence of the system from external N sources.

The spatial distribution of the water input into the soil as a driving variable of nutrient leaching depends on the crown hydrology of the tree species present and their spatial arrangement. Certain tree species, such as palms, concentrate significant amounts of rainwater around their trunk in the form of stemflow. In high-rainfall areas, such species could be used to increase water infiltration in some spots in a plot and reduce it in others, thereby separating zones with high infiltration from zones with high concentration of soluble nutrients in the soil.

Leached nutrients could be recycled through the integration of deep-rooting trees, but it must be kept in mind that in forest areas where multi-strata agroforestry predominates, farmers may not be willing to plant trees for ecological functions only, unless these offer at the same time perceptible economic advantages. Recent evidence suggests that oil palms are efficient in capturing N from the soil. The integration of such ecologically and economically useful species into multi-strata agroforestry systems may also be a way of widening the potential markets for agroforestry products, and this may be a precondition for the transformation of the vast areas of abandoned lands in Amazonia and other tropical forest regions into productive agroforestry systems.

Managing biological agents of soil fertility
Despite the perennial soil cover provided by tree crops and often relatively modest nutrient exports with the harvest, long term degradations of soil fertility under tropical monoculture plantations have often been reported. Although the reasons are not always clear, a potential way of reducing such decline phenomena in multi-strata agroforestry systems may be a judicious management of the biological agents of soil fertility, including plant roots, soil microorganisms and soil fauna. Here we discuss mainly the role and management perspectives of the soil fauna.

Certain groups of the soil macrofauna, such as earthworms and termites, can have a pronounced influence on soil structure, soil organic matter dynamics and litter decomposition and thereby on water and nutrient cycling in the soil. This effect is not always positive - under certain conditions earthworms can build up a very high biomass in the soil and provoke severe soil compactions, as has been observed in Amazonian pastures. So, the objective is not the maximization of soil fauna density or biomass, but the creation of development conditions for an equilibrated and diverse fauna.

The analysis of single-tree effects within agroforestry plots and controlled experiments have shown that tree species differ in their effect on the soil fauna, mainly because of differences in litter quality and quantity as well as microclimatic factors. As a consequence, multi-strata agroforestry systems provide a mosaic of living conditions for the soil and litter fauna, whose abundance, diversity and composition changes over small distances. Management options for improving the living conditions for the soil fauna include the association of tree species with less favourable effects on the fauna with tree and cover crop species with a more favourable effect; the maintenance of an abundant litter or mulch layer; and the provision of suitable microclimatic conditions. The input level, on the other hand, seems to have little direct influence on the soil fauna. Evidence for the potential of multi-strata agroforestry for improving the living conditions of the soil fauna comes from a system in Amazonia which had been established on abandoned pasture land. The vertical distribution of the fauna indicated that niches had become available which disappear when forest is transformed into pastures or fields with annual crops.

Reducing negative interactions
The decision by a farmer to include a certain tree species into an agroforestry system will be based mainly on economic considerations. This is true for tree crops and in many cases also for "service" trees. Central American coffee farmers increasingly plant fast-growing timber trees as shade, instead

of the traditional legume tree species. This economic bias in the decision about the components of agroforestry systems means that these may not always be ideal choices with respect to their combining ability relative to other species in the system. Being fast-growing and productive, the chosen tree species may often also be competitive. Excessive competition for light may be avoided by suitable spacing and eventually pruning of the tree crowns, but root competition is less obvious and more difficult to control. The topic has been treated previously and will not be considered in much detail in this review, but some principles and new developments will be summarized. When designing a system, it is important to keep in mind that maximum efficiency of the use of soil resources can only be achieved when there is a certain level of competition between the root systems present. For example, if the root systems of neighboring trees do not overlap sufficiently, N mineralized under the cover crop between them may be leached unproductively, and P which is available in the soil may not be taken up because of insufficient root length density. On the other hand, if the rooting density is considered sufficient in a certain zone, it would be advantageous to reduce the entry of other species' root systems into this zone. Sometimes this can be achieved through wider spacing, but when the shade of the species is needed, other methods need to be sought. Recently it has been demonstrated that simple grass strips can strongly modify the root distribution of some tree species. The potential of this technique for subdividing the soil within multi-strata systems into "compartments" is currently being studied in Costa Rica. Before applying such techniques, it is crucial to know which root functions are expected from a certain species, because where the roots have been excluded, they can not participate any more in nutrient capture or other soil improvements.

Conclusions

Plant-soil interactions in multi-strata agroforestry systems have received insufficient attention by researchers in the past, presumably because of methodological difficulties. Using the methodological principles outlined above, more research efforts should be invested in these systems, taking into consideration the following issues:

a) How much competition between associated plants is necessary for optimum use of soil resources? How can competition be monitored and fine-tuned within agroforestry systems with perennial crops?
b) Fertilizer use efficiency of whole systems as influenced by different tree components and management practices.
c) Establishment methods for plantations which favour the development of the tree crops, taking into consideration the limited funds of many tropical smallholders.
d) Possibilities to manage the biological agents of soil fertility, especially the quantification of the agronomic value of soil biodiversity and methods of conserving and increasing it in agroforestry systems.